Electrospray mass spectrometry evidence for an oxo-manganese(V) species generated during the reaction of manganese triazacyclononane complexes with H_2O_2 and 4-methoxyphenol in aqueous solution

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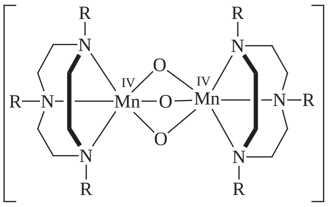
Electrospray mass spectrometry has been used to identify the formation of oxo-manganese(V) species in the oxidation of 4-methoxyphenol by H_2O_2 catalysed by manganese 1,4,7-triazacyclononane complexes in aqueous solution.

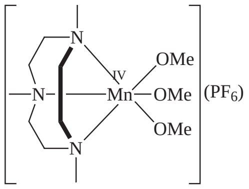
There has been considerable recent interest in the preparation and properties of dinuclear manganese complexes, especially in relation to their potential use as industrial oxidants and as models for enzyme action (*e.g.* model complexes for the oxygen-evolving complex in photosystem II and catalases).[1] Some of these, such as manganese 1,4,7-triazacyclononane complexes, have also been shown to be effective catalysts for the oxidation of a variety of organic substrates with hydrogen peroxide.[2] However, very little is known about the mechanisms or the active oxidants in these systems: high-valent manganese or oxo-manganese species (mono- or di-nuclear) and/or oxygen-centred radicals could all be involved. Indeed, in a very recent paper Barton has suggested the formation of a $Mn^V{=}O$ intermediate during the oxidation of 2,6-di-*tert*-butylphenol with $[L_2Mn^{IV}_2(\mu\text{-}O)_3(PF_6)_2]$, L = 1,4,7-trimethyl-1,4,7-triazacyclononane (TMTACN) (**1a**) and H_2O_2.[3] Our investigations of the reaction of electron-rich phenols with **1a**, in the absence and presence of H_2O_2 in aqueous solution (pH 10.5), show that the initial reaction involves a single electron transfer from the phenolate ion to **1a** resulting in the formation of a paramagnetic dinuclear Mn^{III}/Mn^{IV} species and the corresponding phenoxyl radical (detected by EPR and UV–VIS spectroscopy).[4]

The aim of the research described here was to obtain more detailed evidence for intermediates other than EPR-detectable species in these and related systems. We describe important new evidence obtained using electrospray mass spectrometry (ES-MS) which is a valuable tool for the investigation of charged metal complexes in both organic and aqueous solution[5] and whose effectiveness has already been demonstrated in mechanistic studies of oxidations catalysed by iron tris(2-pyridylmethyl)amine and manganese salen complexes.[6,7]

The experiments involved the di- and mono-nuclear complexes **1a** and **2** and also the combination of $MnSO_4$ with free TMTACN ligand. They were carried out using aqueous solutions (borate buffer, pH 10.5) of the Mn–TMTACN complexes (1×10^{-5} mol dm^{-3}) with an excess of 4-methoxyphenol (100-fold over Mn complex) and in the presence and absence of H_2O_2 (1000-fold excess over Mn complex) at 60 °C. All mass spectra were acquired by syringe pump infusion of an aliquot of a reaction mixture into a Finnigan LCQ mass spectrometer equipped with an electrospray interface.



1a R = CH_3
1b R = C_2H_5



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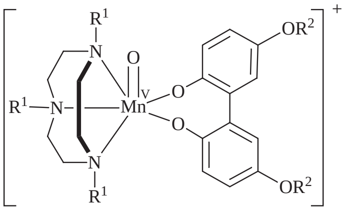
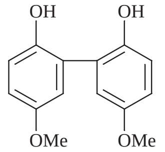


3a $R^1 = R^2 = CH_3$
3b $R^1 = C_2H_5$ $R^2 = CH_3$
3c $R^1 = CH_3$ $R^2 = C_2H_5$



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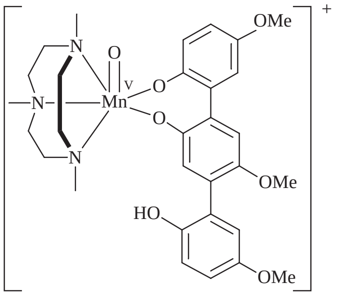

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The ES mass spectrum of **1a** in aqueous solution in the absence of substrate and H_2O_2 shows characteristic peaks with $m/z = 645$ (base peak), identified as $[L_2Mn^{IV}_2(\mu\text{-}O)_3(PF_6)]^+$, and $m/z = 250$, typical of $[L_2Mn^{IV}_2(\mu\text{-}O)_3]^{2+}$ [see Fig. 1(a)]. On addition of 4-methoxyphenol we observed (after *ca.* 5 min) a new base peak with $m/z = 500$ assigned to $[L_2Mn^{III/IV}_2(\mu\text{-}O)_3]^+$ with residual peaks of unreacted **1a** [see Fig. 1(b)]; after *ca.* 20 min the spectrum showed the appearance of a dominant peak at $m/z = 172$ due to $[LH]^+$ with a minor peak from $[LNa]^+$ ($m/z = 194$). These observations are broadly in agreement with our EPR-based mechanistic proposal that electron transfer from the substrate to **1a** gives a dinuclear Mn^{III}/Mn^{IV} species and, ultimately, monomeric Mn^{II} and free ligand.[4]

Repeating the reaction in the presence of H_2O_2 gave, after 5 min, a new singly charged species with $m/z = 486$ and

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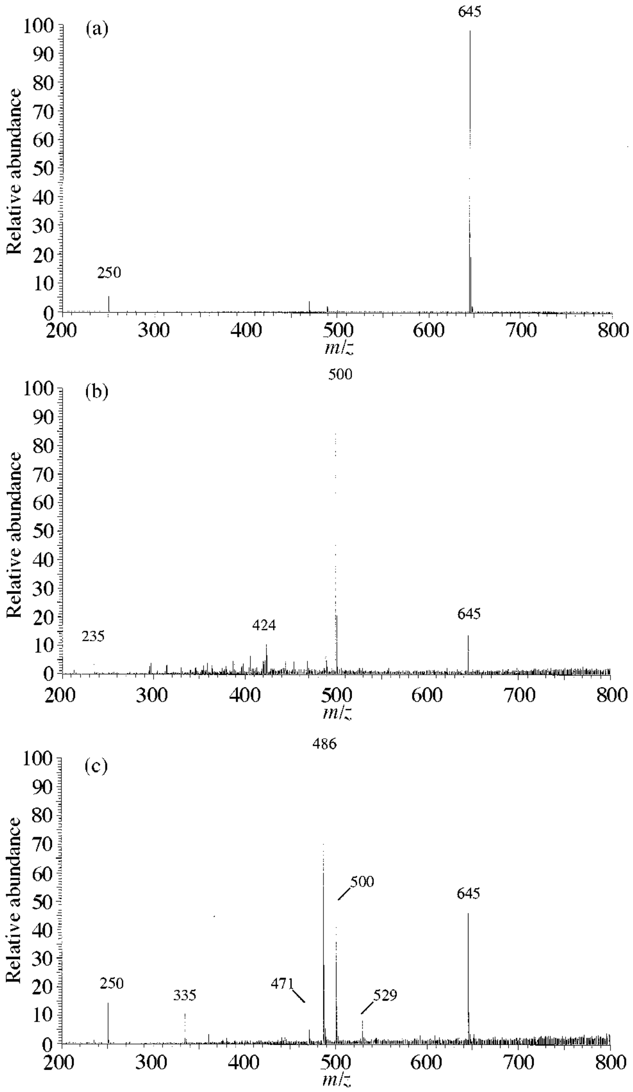

Fig. 1 Electrospray mass spectrum of (a) an aqueous solution (pH 10.5) of $[L_2Mn^{IV}_2(\mu\text{-}O)_3(PF_6)_2]$, L = 1,4,7-trimethyl-1,4,7-triazacyclononane, (b) after 5 min reaction at 60 °C with 4-methoxyphenol and (c) after 5 min reaction at 60 °C with 4-methoxyphenol and H_2O_2

smaller peaks (m/z = 645 and 500) from residual $[L_2Mn^{IV}_2(\mu\text{-}O)_3(PF_6)]^+$ and $[L_2Mn^{III/IV}_2(\mu\text{-}O)_3]^+$ [Fig. 1(c)]. When during the injection into the ES-MS detector MeOH was used as sheath liquid,‡ further singly charged species were also detected at m/z = 608, 730 and 852. Increasing the reaction time to 15 min before analysis resulted in an ES mass spectrum that consisted solely of the singly charged species at m/z = 486. After 30 min only ions with m/z = 172 and 194, $[LH]^+$ and $[LNa]^+$ respectively, were detected.

Replacing **1a** with the mononuclear complex $[LMn^{IV}(OMe)_3(PF_6)]$ (**2**) or with $MnSO_4$ and the free TMTACN ligand, under the same conditions, also resulted in the formation (after 5 min) of the singly charged reaction intermediates m/z = 486, 608, 730 and 852 which after 30 min reacted further to give $[LH]^+$ (m/z = 172) and $[LNa]^+$ (m/z = 194).

It is noteworthy that in all the systems described above the species with m/z = 486, 608, 730 and 852 were not generated in the absence of H_2O_2.

The assignment of the species with m/z 486 to the intermediate **3a** $[LMn^V(O)(5,5'\text{-dimethoxy-}2,2'\text{-bisphenolate})]^+$ is based in part on our observation of 2,2′-dihydroxy-5,5′-dimethoxybiphenyl (**4**) as the major product (formed *via* radical dimerisation) in the oxidation of 4-methoxyphenol with **1a** with H_2O_2, and on the following observations.[4]

Firstly, in ES-MS experiments with the ethyl analogue of **1a**: $[L'_2Mn^{IV}_2(\mu\text{-}O)_3(PF_6)_2]$, L′ = 1,4,7-triethyl-1,4,7-triazacyclononane (**1b**) in the absence of H_2O_2 and substrate the major ion detected had m/z = 729 assigned to $[L'_2Mn^{IV}_2(\mu\text{-}O)_3(PF_6)]^+$ with a minor peak (m/z = 292) resulting from the doubly charged species $[L'_2Mn^{IV}_2(\mu\text{-}O)_3]^{2+}$. Addition of 4-methoxyphenol gave (after 5 min) a new species (m/z = 584) we assign to $[L'_2Mn^{III/IV}_2(\mu\text{-}O)_3]^+$ and, after 20 min, $[L'H]^+$ (m/z = 214). Reaction of **1b** with 4-methoxyphenol in the presence of H_2O_2 resulted (after 5 min) in the formation of a species with m/z = 528; the use of MeOH as sheath liquid led to the detection of singly charged species at m/z = 650, 772 and 894 and after 20 min the ES mass spectrum changed to that of $[L'H]^+$ (m/z = 214). The species m/z = 528 from the **1b**–4-methoxyphenol–H_2O_2 system corresponds to the expected *N*-ethyl analogue of **3a**, $[L'Mn^V(O)(5,5'\text{-dimethoxy-}2,2'\text{-bisphenolate})]^+$ (**3b**).

The species that are detectable when methanol is used as sheath liquid can be assigned to tri-, tetra- and pentaoligophenol analogues of **3a** and **3b** (see for example **5** m/z = 608, with the triphenolic ligand generated from 4-methoxyphenol). The 122 mass difference between these species corresponds to a 4-methoxyphenol unit in the oligophenol.

Secondly, 4-ethoxyphenol, in the absence of H_2O_2, gave the same species with **1a** as described above for 4-methoxyphenol, indicating that both phenols react in the same way. Repeating the reaction in the presence of H_2O_2 resulted (after 5 min) in the formation of the expected diethoxy analogue of **3a** $[LMn^V(O)(5,5'\text{-diethoxy-}2,2'\text{-bisphenolate})]^+$ (**3c**) with m/z = 514. Furthermore, species at m/z = 650, 786 and 922 corresponding to the tri-, tetra- and pentaoligophenol analogues of m/z = 514 were also detected. After 20 min the ES mass spectrum of the protonated ligand $[LH]^+$ (m/z = 172) was observed.

Thirdly, when the reaction of 4-methoxyphenol and **1a** was carried out in the presence of $H_2{}^{18}O_2$ (90 atom% ^{18}O), ES-MS showed the major peak at m/z = 488 which we assign to $[LMn^V(^{18}O)(5,5'\text{-dimethoxy-}2,2'\text{-bisphenolate})]^+$; when the complementary experiment was carried out with H_2O_2 in ^{18}O labelled water (20 atom% ^{18}O) there was no incorporation of the isotopic label into the intermediate. These experiments identify hydrogen peroxide as the source of the oxo-oxygen. The labelled oligophenol analogues of **3a** with m/z = 610, 732, 854 and 976 were also detected from the $H_2{}^{18}O_2$ reaction and it is noteworthy that the mass difference between the oligophenols is 122, indicating that no ^{18}O is incorporated in the phenolic ligand.

With these ES-MS experiments we have been able to characterise for the first time a mononuclear oxo-manganese(V) intermediate in an oxidation with the dinuclear Mn–TMTACN complex **1a** and H_2O_2. We have also shown that this species can be generated in analogous oxidations using H_2O_2 with the mononuclear Mn^{IV} complex **2** and with Mn^{II} with free TMTACN ligand.

Our previous results showed that **1a** is reduced by 4-methoxyphenol *via* an Mn^{III}/Mn^{IV} complex to mononuclear Mn^{II} in a series of single-electron transfers. The phenoxyl radicals generated in this process dimerise to give an *ortho,ortho*-biphenol and we believe this forms a chelate complex with the mononuclear manganese which is subsequently oxidised with H_2O_2 to give the $Mn^V{=}O$ species **3a** [*cf.* the oxidation of manganese(III) to oxo-manganese(V) in the related reactions of manganese salens[7] and porphyrins[8]]. We suggest that the detection of **3a** reflects two aspects of the methoxy group in the substrate. First, by electron donation it encourages the initial electron transfer and in the dimer ligand it stabilises the $Mn^V{=}O$. Secondly, by blocking the 4-position it favours coupling to give the *ortho, ortho*-biphenol. The importance of the *ortho,ortho*-biphenol

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‡ The sheath liquid can stabilise and enhance the ES process for some solutions (for example, those with a high aqueous content) that do not readily form an electrospray.

ligand has been confirmed by reacting **1a** with H_2O_2 in the presence of 2,2′-dihydroxybiphenyl which led to the formation of both the 2,2′-dihydroxybiphenyl analogue of **3a** and to the Mn^{III} species $[LMn^{III}(2,2'\text{-bisphenolate})]^+$.

Currently we are exploring the potential of phenolic ligands for stabilising high-valent oxo-manganese species with the aim of using the biphenolic template to control the catalytic activity and selectivity of these manganese catalysts.

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References

1 (*a*) R. Hage, J. E. Iburg, J. Kerschner, J. H. Koek, E. L. M. Lempers, R. J. Martens, U. S. Racherla, S. W. Russell, T. Swarthoff, M. R. P. van Vliet, J. B. Warnaar, L. van der Wolf and L. B. Krijnen, *Nature*, 1994, **369**, 637; (*b*) V. L. Pecoraro, A. Gelasco and M. J. Baldwin, *Adv. Chem. Ser.*, 1995, **246**, 265; (*c*) G. C. Dismukes, *Chem. Rev.*, 1996, **96**, 2909.

2 (*a*) R. Hage, *Recl. Trav. Chim. Pays-Bas*, 1996, **115**, 385; (*b*) V. C. Quee-Smith, L. DelPizzo, S. H. Jureller, J. L. Kerschner and R. Hage, *Inorg. Chem.*, 1996, **35**, 6451; (*c*) D. E. De Vos and T. Bein, *J. Organomet. Chem.*, 1996, **520**, 195; (*d*) D. E. De Vos, J. L. Meinershagen and T. Bein, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 2211; (*e*) C. Zondervan, R. Hage and B. L. Feringa, *J. Chem. Soc., Chem. Commun.*, 1997, 419; (*f*) C. Bolm, D. Kadereit and M. Valacchi, *Synlett*, 1997, 687; (*g*) J. R. Lindsay Smith and G. B. Shul'pin, *Tetrahedron Lett.*, 1998, **39**, 4909.

3 D. H. R. Barton, S.-Y. Choi, B. Hu and J. A. Smith, *Tetrahedron*, 1998, **54**, 3367.

4 B. C. Gilbert, N. W. J. Kamp, J. R. Lindsay Smith and J. Oakes, *J. Chem. Soc., Perkin Trans. 2*, 1997, 2161.

5 (*a*) J. W. Sam, X.-J. Tang and J. Peisach, *J. Am. Chem. Soc.*, 1994, **116**, 5250; (*b*) J. W. Sam, X.-J. Tang, R. S. Magliozzo and J. Peisach, *J. Am. Chem. Soc.*, 1995, **117**, 1012; (*c*) U. N. Anderson, C. J. McKenzie and G. Bojesen, *Inorg. Chem.*, 1995, **34**, 1435; (*d*) C. P. Horwitz, J. T. Warden and S. T. Weintraub, *Inorg. Chim. Acta*, 1996, **246**, 311.

6 C. Kim, K. Chen, J. Kim and L. Que, *J. Am. Chem. Soc.*, 1997, **119**, 5964.

7 D. Feichtinger and D. A. Plattner, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 1718.

8 J. T. Groves, J. Lee and S. S. Marla, *J. Am. Chem. Soc.*, 1997, **119**, 6269.

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